Laser-based Space Debris Mitigation in the Low Earth Orbit

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OSA Laser Applications Conference,
Vienna, September 30, 2019

Overview

Introduction to…

… the threat caused by space debris

… and concepts for its remediation

Review on constraints …

… related to laser-debris interaction

… and ground-based laser operation

Near-term steps at DLR Institute of Technical Physics

Conclusion

The space debris threat

DLR

Hazardous Space Debris Objects

Objects > 10 cm

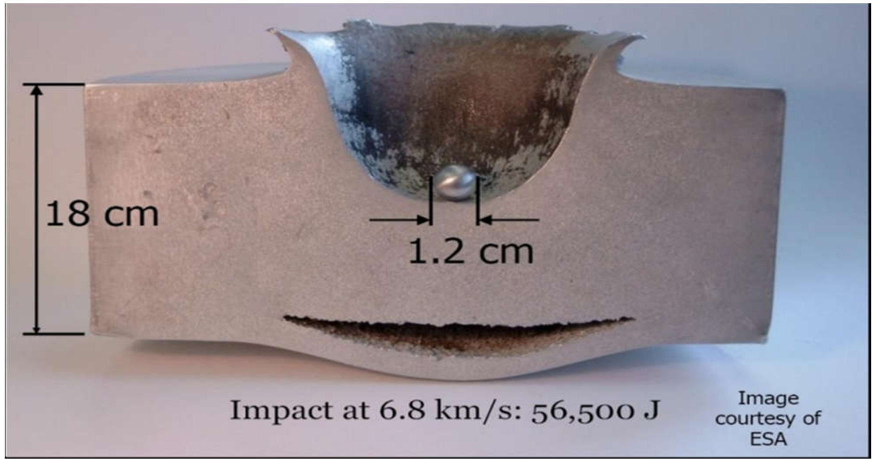
- Fragments, Rocket bodies, Defective satellites
- s/c destruction (→ Kessler syndrome)
- Monitoring & obstacle avoidance possible
- ≥ 5 cm: 16,809 catalogued ***and published*** TLE

Active satellites and debris objects > 10 cm in Earth orbit

Objects between 1 cm and 10 cm

main ROI for laser-based removal

- s/c wall penetration (→ loss of functionality)
- Difficult to detect
- 500,000 – 1,000,000 objects (estimated)

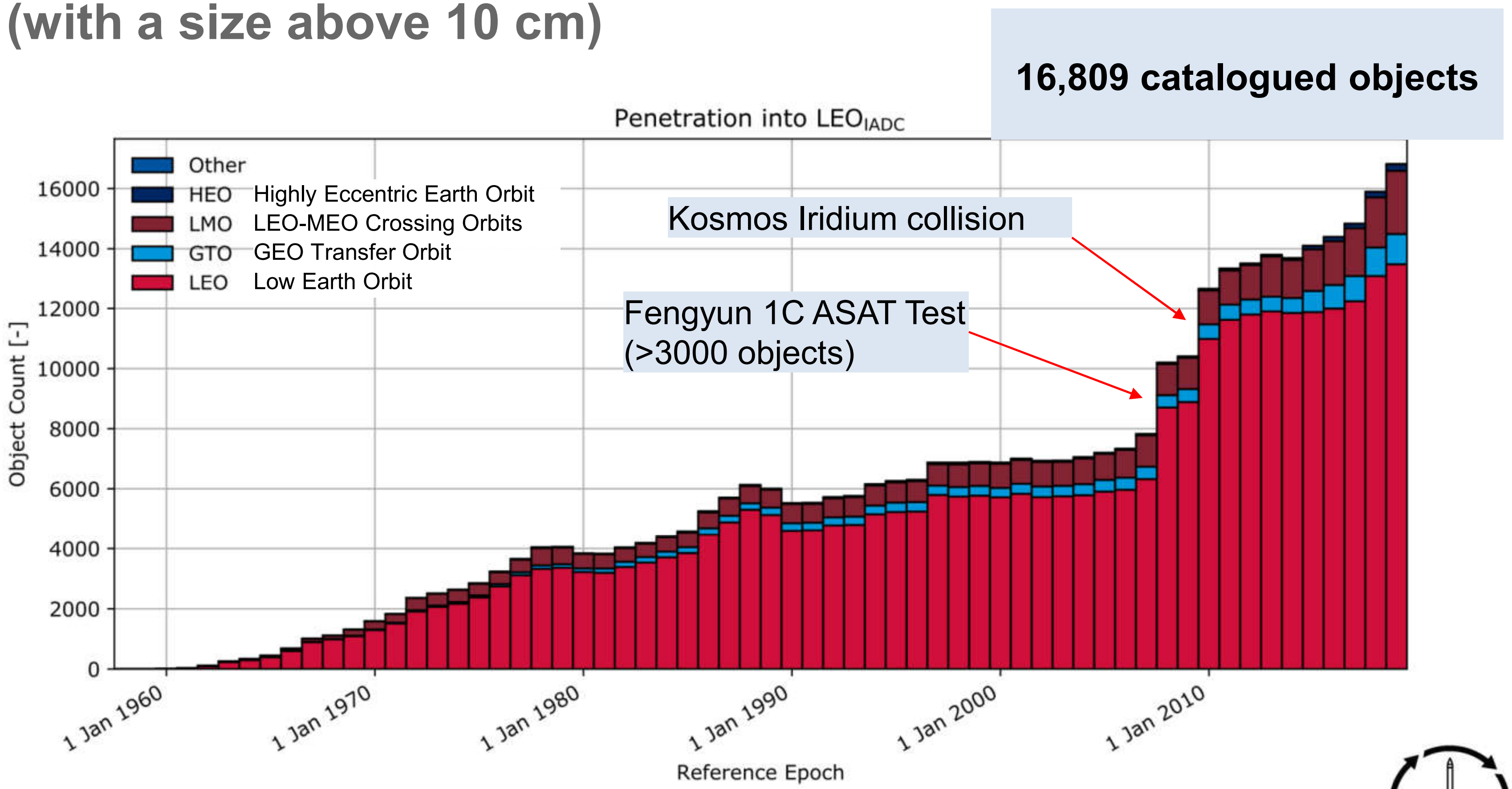


Impact of aluminum sphere in aluminum block @ 6.8 km/s

Objects between 1 mm and 1 cm

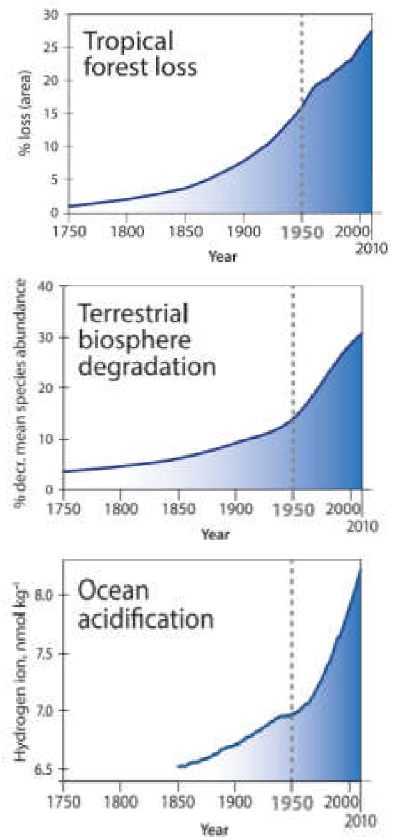
- 200,000,000 objects
- s/c damage (→ loss of performance)
- No detection possibilities

Temporal development of catalogued orbital objects in LEO (with a size above 10 cm)



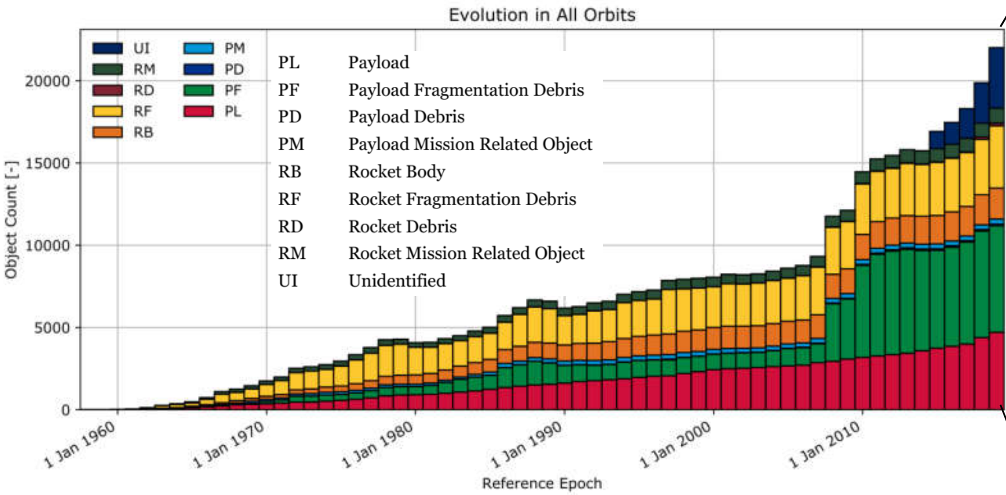
ESA's Annual Space Environment Report
Issue Date 17 July 2019 Ref GEN-DB-LOG-00271-OPS-SD
ESA Space Debris Office, European Space Operations Centre (ESOC), Darmstadt

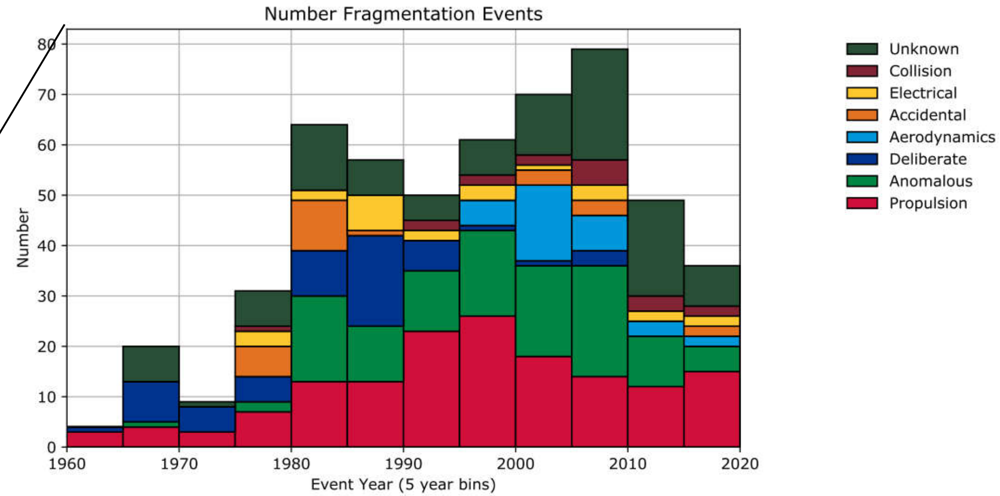
Earth system trends (Environmental stressors)



Trends taken from: T. Maury et al., Integrating space debris modeling to environmental impact studies via the Life Cycle Assessment framework, CNES workshop on Space Debris Modeling and Remediation, Paris, 2018

Fragmentation Debris





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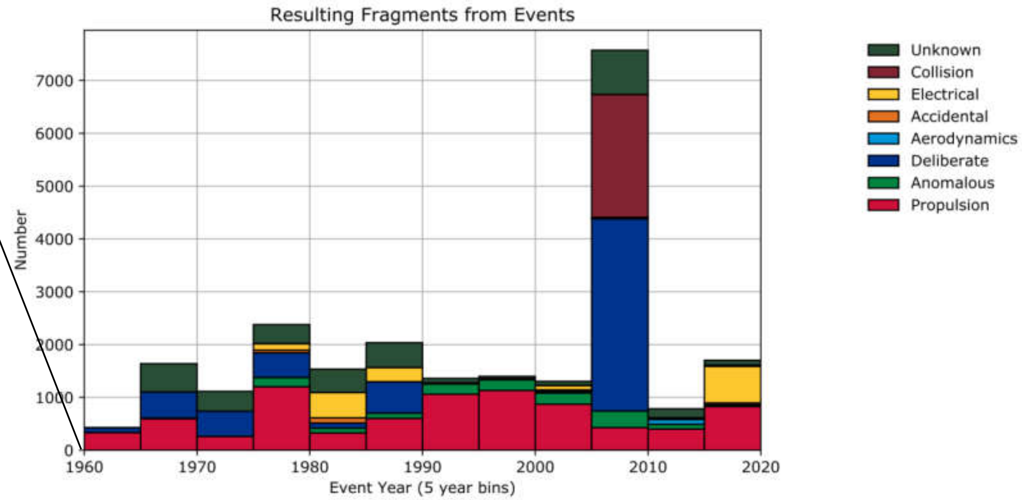
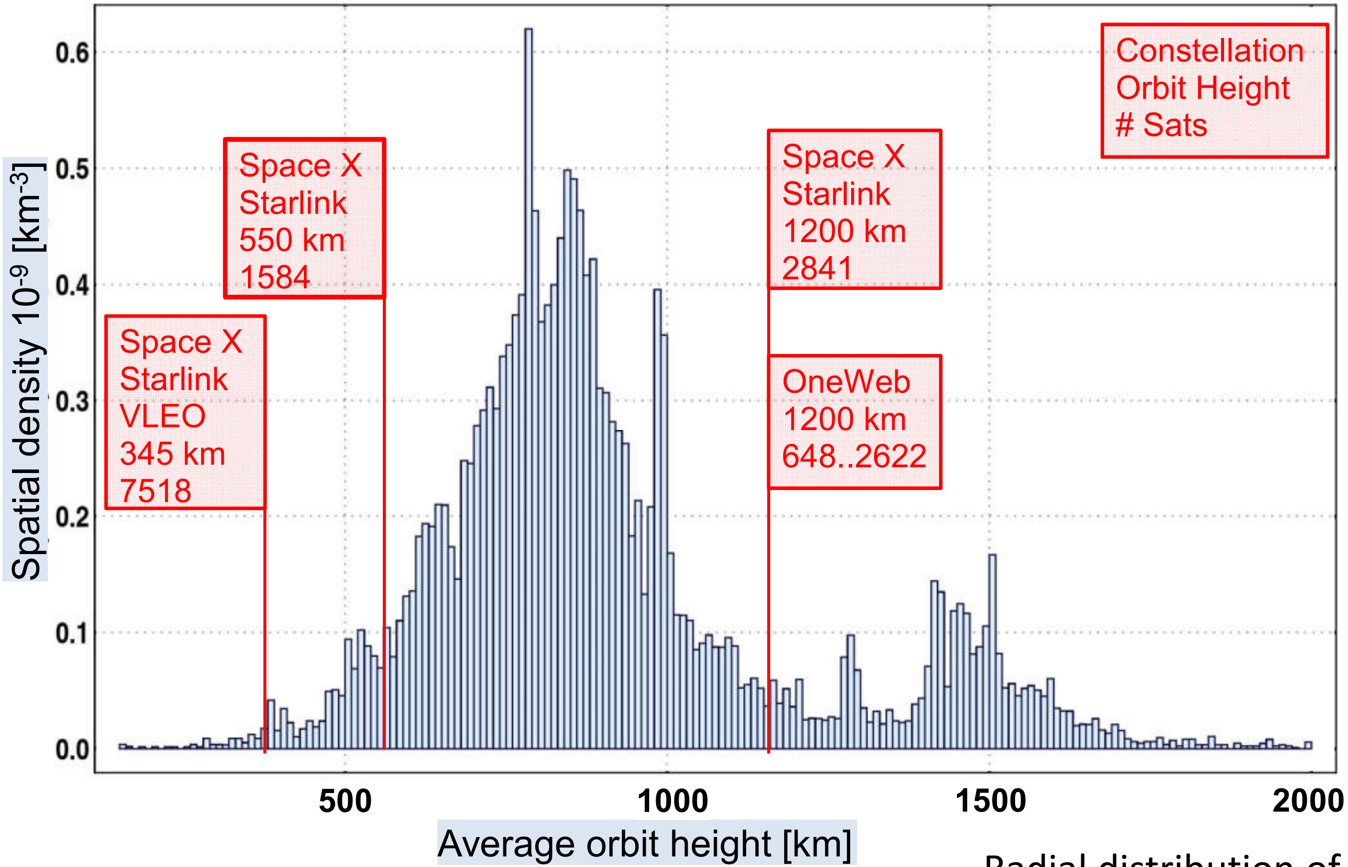


$$N\_Fragments_{Event\ \#1}$$
$$+N\_Fragments_{Event\ \#2}$$
$$= ???$$

Is there still space in space?



Mega Constellations

SpaceX Starlink (US)
11,943 Sats (62 in orbit as of 24/05/19)
V & Ka band & in-orbit LaserCom

OneWeb (UK)
648 -> 2,622 Sats (6 in orbit as of 27/02/19)
Ku band

Sum: 14,565 Sats, FCC approved

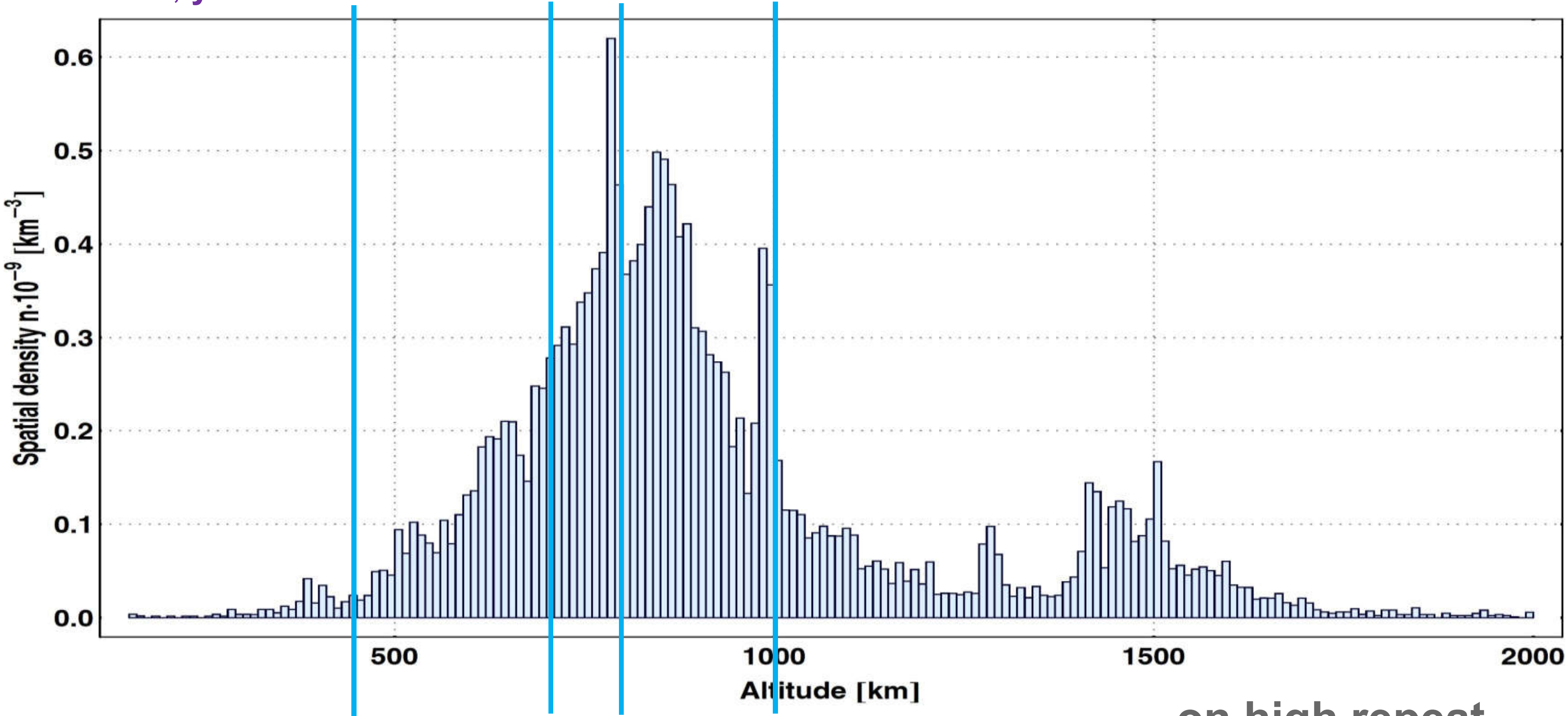
Amazon „Project Kuiper“
(announced 04/2019)
3,236 Sats

Radial distribution of catalogued orbital objects in LEO
(sized above 10 cm - including Mega Constellations)

In the Lower Earth Orbit, everything is for a long time …

Orbital residence time, **years**: 1 25 100 1000

… and there is less space than it may seem.



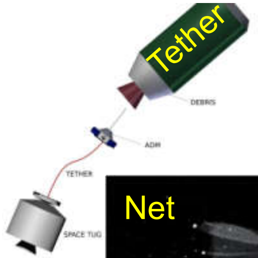
Orbit period, **minutes**: 94 99 101 106

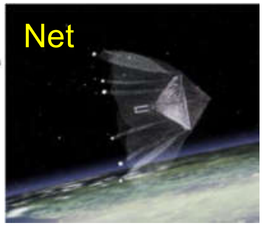
… on high repeat …

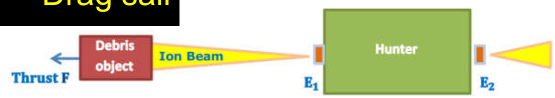
Space debris remediation concepts

DLR

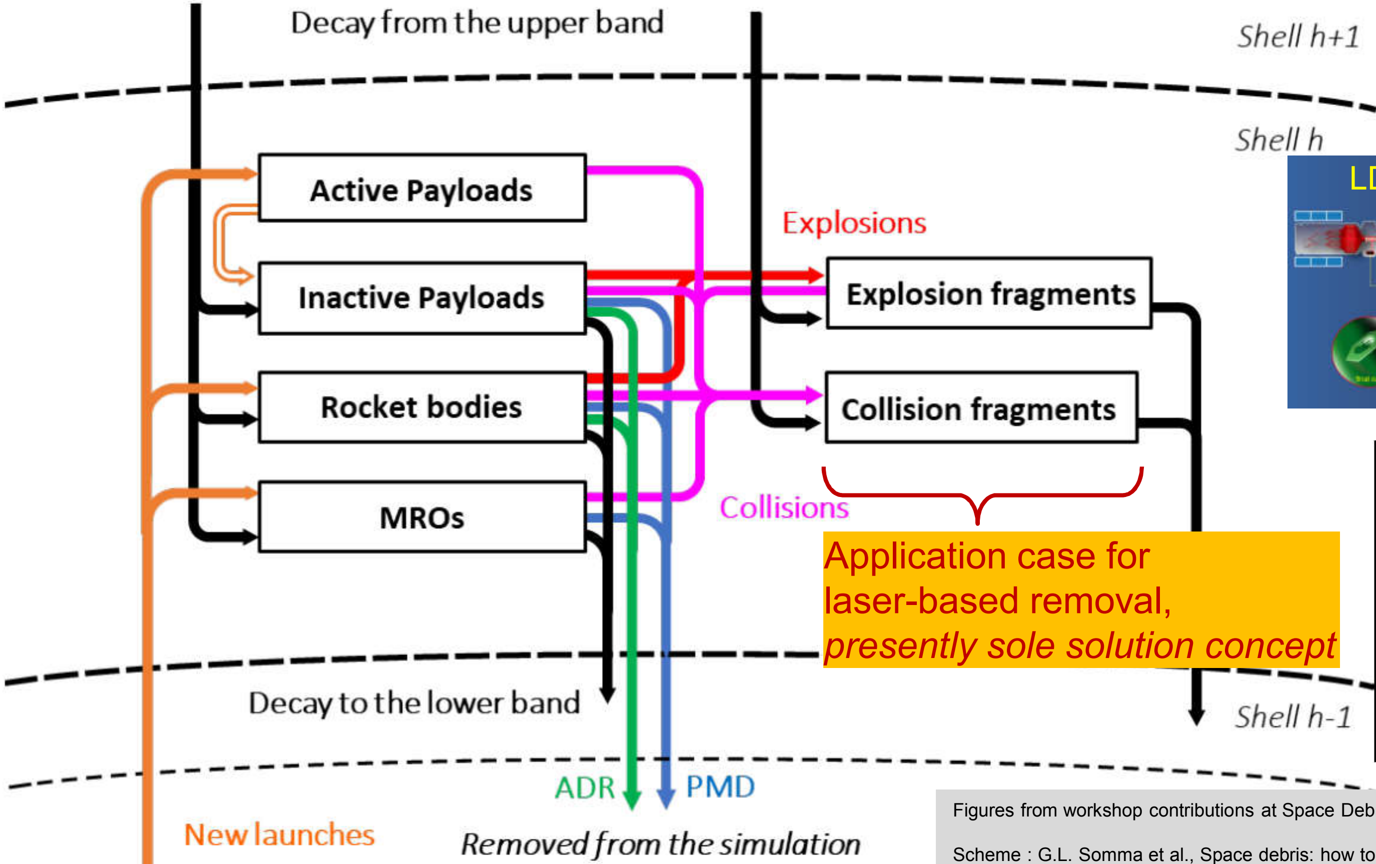
Space debris removal concepts

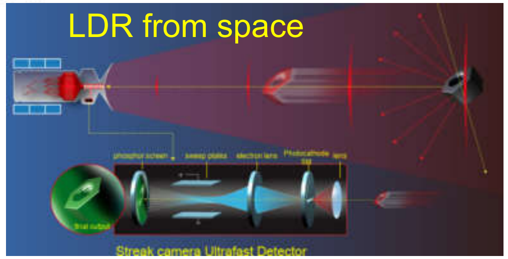


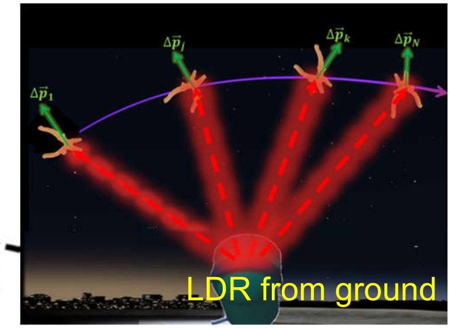




Ion beam







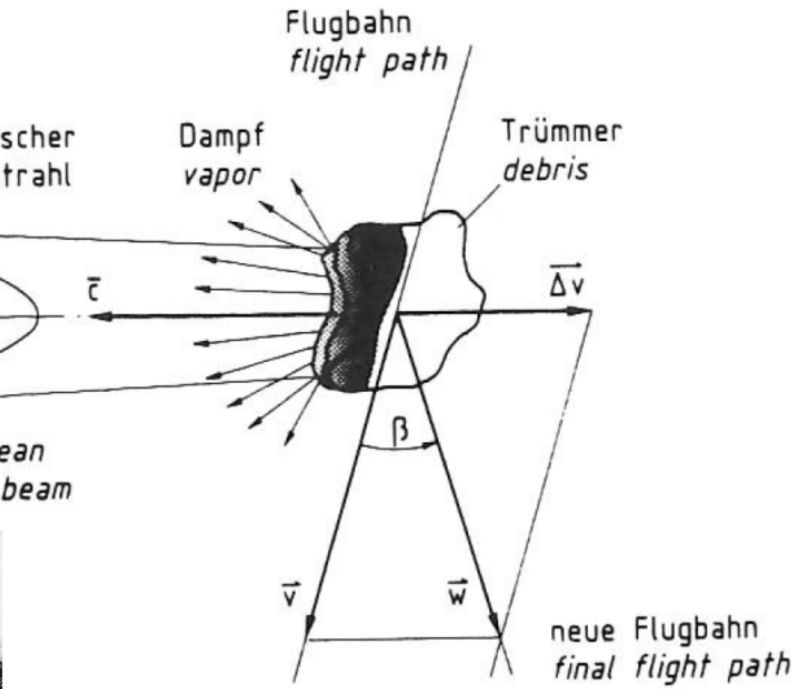
PMD: post-mission disposal
ADR: active debris removal

Figures from workshop contributions at Space Debris Modeling and Remediation, CNES Paris, 2018

Scheme : G.L. Somma et al., Space debris: how to increase the active removal effectiveness
Tether: V. Trushlyakov et al., Progress-M spacecraft as the basis for the space tug for ADR missions
Net, harpoon, drag sail: Aglietti et al., Removedebris preliminary mission results
Ion beam: Cui et al., Removal of Geostationary Debris
Space-based LDR: J.-C. Chanteloup, High average/peak powers laser architecture based on Coherent Beam Combining of fiber amplifiers for space applications
Ground-based LDR: S. Scharring et al., Removal of Small-Sized Space Debris by Laser-Ablative Momentum Generation

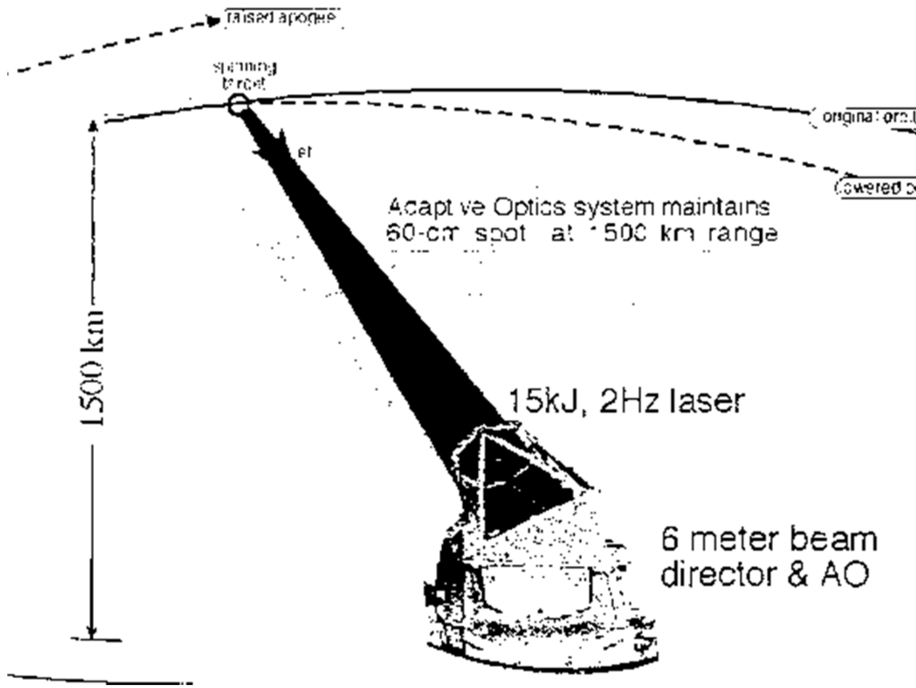
The Early Concepts of Laser-based Space Debris Removal

Space-based LDR (Wolfgang Schall, 1991)



W. Schall, "Orbital debris removal by laser radiation," Acta Astronaut. 24, 343–351 (1991). [doi:10.1016/0094-5765(91)90184-7]

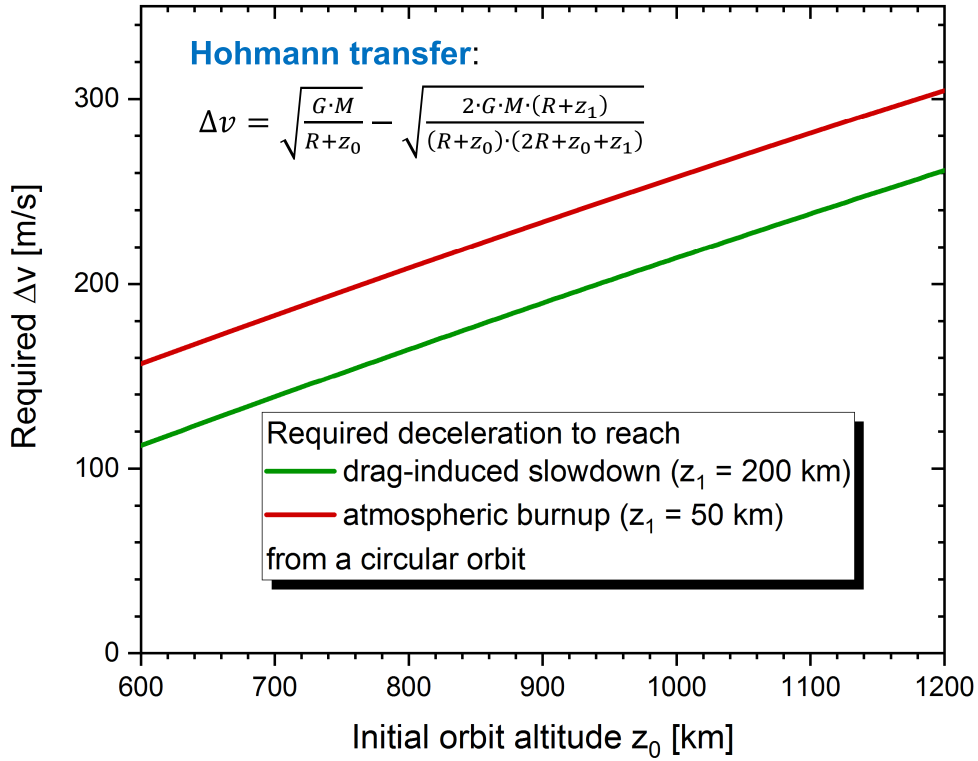
Earth-based LDR (Claude R. Phipps, 1996)



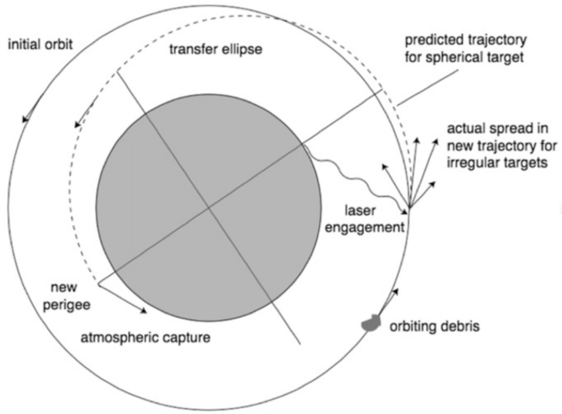
C.R. Phipps et al., „Orion: Clearing Near-Earth Space Debris Using a 20 kW, 530 nm, Earth-Based, Repetitively Pulsed Laser," Laser and Particle Beams **14**(1): 1-44 (1996)

Astrodynamics Constraints

Target deceleration for atmospheric burn-up



In-track / radial momentum transfer



$$H = \frac{v_v^2 + v_r^2}{2} - \frac{G \cdot M}{r}$$

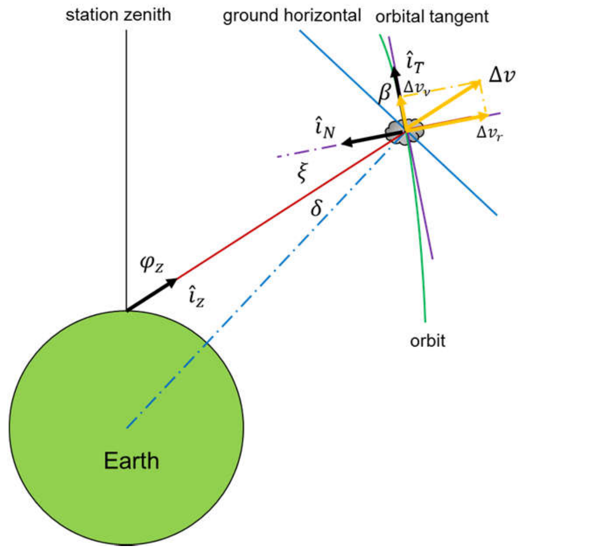
$$\Delta a = \frac{G \cdot M}{2H^2} \Delta H$$

$$\Delta r_p = (1-\varepsilon)\Delta a - a\Delta\varepsilon$$

$$\Delta r_a = (1+\varepsilon)\Delta a + a\Delta\varepsilon$$

C.R. Phipps et al., Removing orbital debris with lasers, Adv. Space Res. **49**: 1283 (2012)

Apogee lift + perigee lowering



adapted from: C.R. Phipps et al., Removing orbital debris with lasers, Adv. Space Res. **49**: 1283 (2012)

Laser-debris interaction constraints

DLR

Requirements:
- High laser pulse energy
- Small laser spot size

Laser fluence in ablative momentum coupling

Main requirement: Laser **fluence** *at the target surface*

$$\Delta v = \eta_c \cdot c_m \cdot \Phi \cdot A_{cs}/m$$

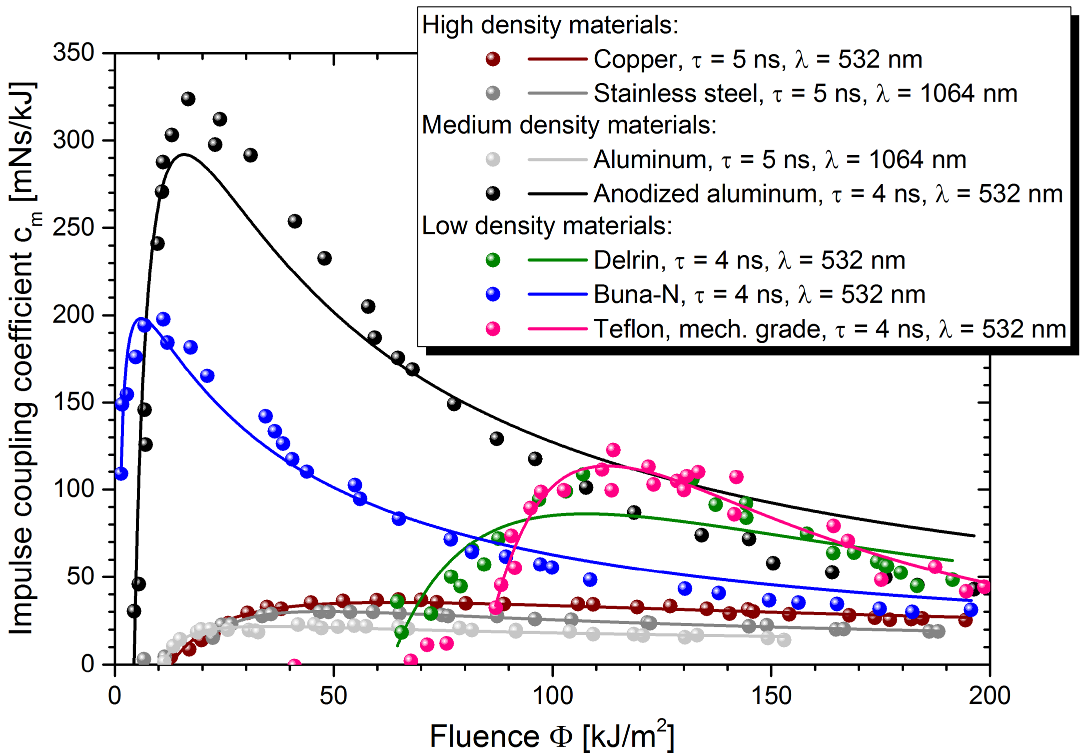
C. Phipps, Acta Astronaut. **93**: 418 (2014)

Key dependency: $c_m(\Phi) \approx \frac{\Phi-\Phi_0}{a+(\Phi-\Phi_0)} \cdot b \cdot 12.46 \cdot A^{7/16} \cdot \left(\frac{\sqrt{\tau}}{\lambda \cdot \Phi}\right)^c$

S. Scharring et al., Opt. Eng. **58**(1): 011004 (2018) following C. Phipps et al., J. Propul. Power **26**: 609 (2010)

Data for $\lambda = 1064\ nm$	Type	τ $[ns]$	Φ_0 $[J/cm^2]$	$c_{m,max}$ $[mNs/kJ]$	$\Phi_{opt}(c_{m,max})$ $[J/cm^2]$
Stainless steel	Exp.	5	1.7	30	4.8
Copper	Exp.	5	2.6	18	36
Aluminum	Exp.	5	2.2	24	8.4
Aluminum	Exp.	8	1.5	13	6.5
Aluminum	Mod.	1	1.1	24	3.5
Aluminum	Mod.	10	3.0	18	10.4

- Typical fluence ($\tau = 5 \ldots 10$ ns, λ = 1064 nm): $\approx 5 - 10\ J/cm^2$
- Threshold fluence: $\Phi_0 \propto \sqrt{\tau}$, dependencies: λ, τ, material



Experimental data from:
B.C. D'Souza, Development of Impulse Measurement Techniques for the Investigation of Transient Forces du Laser-Induced Ablation, PhD Thesis, University of Southern California (2007)

Requirements:
- Material reconnaissance
- Shape information
- Knowledge of orientation

Momentum uncertainty

Laser-matter interaction code

EXPEDIT

EXamination **P**rogram for irr**E**gularly shape**D** debr**I**s **T**argets

$$\vec{p} = \sum_j \vec{p_j} = \sum_j -c_m(\Phi_L, \vartheta) \cdot \Phi_L(\vec{r}) \cdot \cos\vartheta_j(\vec{r}) d\hat{n}_j(\vec{r})$$

S. Scharring et al., Opt. Eng. **58**(1): 011004 (2018)

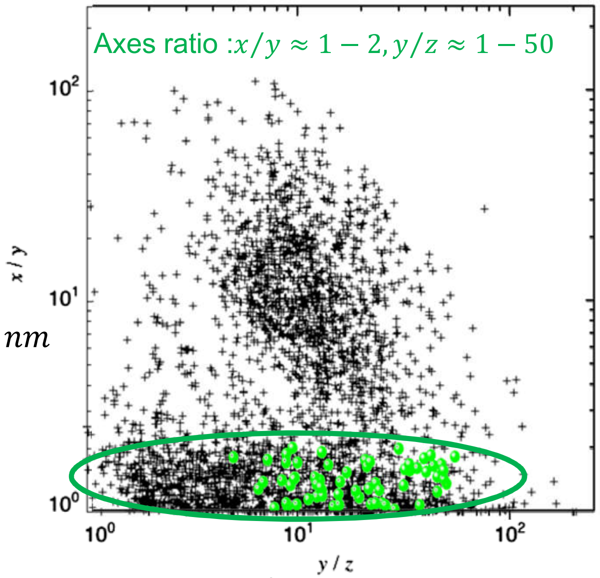
Laser: $\Phi = \Phi(\vec{r})$
Matter: *Finite surface elements (obj files)*
Interaction: $c_m(\Phi), \eta_{res}(\Phi)$

Simulation setup

- Laser specs: $E_L = 25\ kJ$, $\tau = 10\ ns$, $\lambda = 1064\ nm$
- Spot: $\emptyset = 0.67\ m$, $\langle\Phi\rangle = 7.2\ J/cm^2$
- Beam Discretization: 0.1 mm resolution
- Monte Carlo simulation:
  - Random target orientation
  - 2000 sample shots / target
  - Beam center = Target CMS

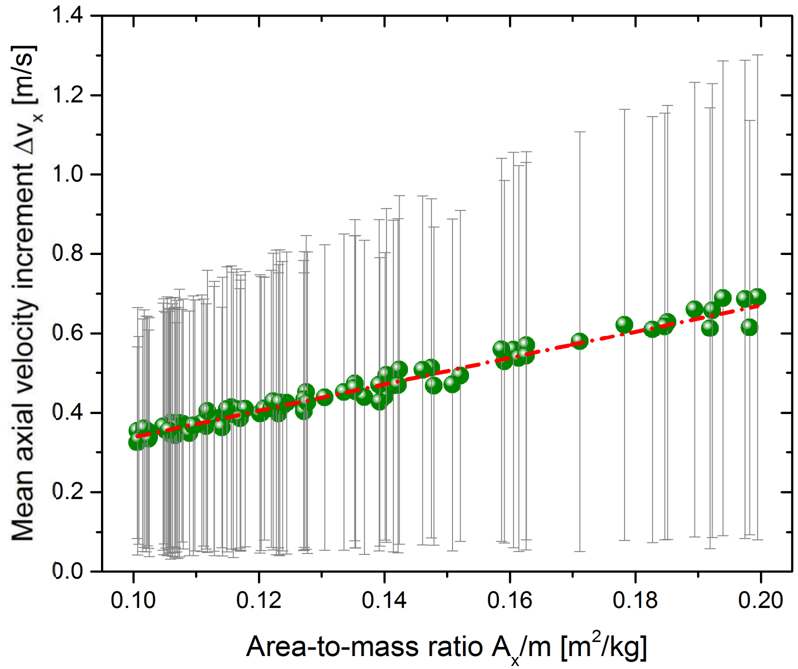
Targets

- 100, randomly generated
- Flake-like ellipsoids
- Material: aluminium
- Size: $L_c \in [0.01\ m; 0.1\ m]$



Targets (green) generated following crash test analysis (black) in:
T. Hanada et al., Adv. Space Res. **44**(5): 558 – 567 (2009)

Velocity Increment Δv



S. Scharring et al., Opt. Eng. **58**(1): 011004 (2018)

→ Consideration of large momentum scatter necessary
→ Collision analysis for conceivable trajectories required

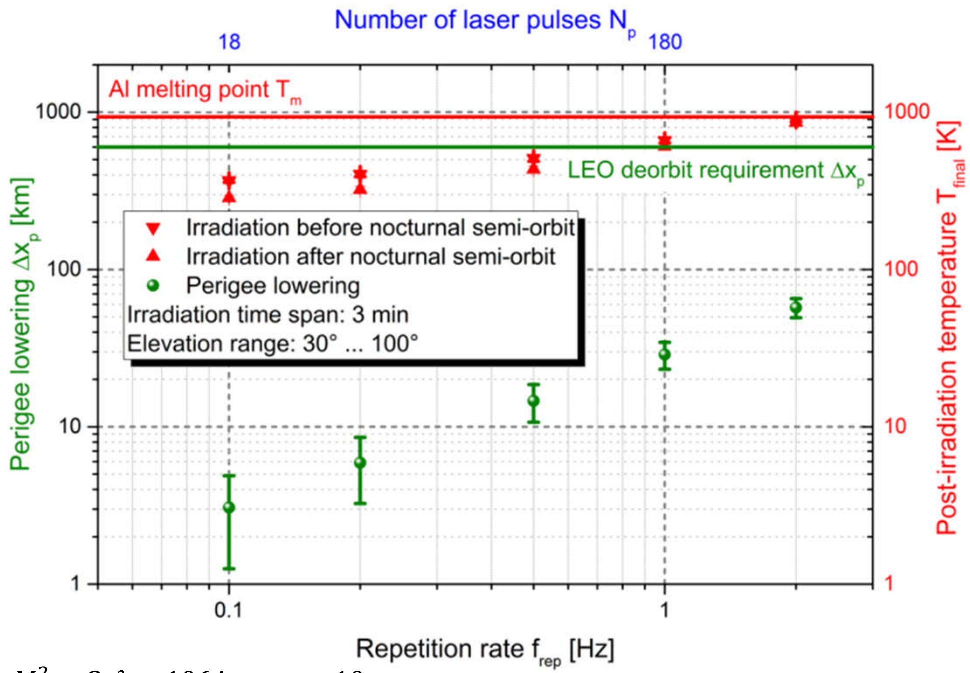
Requirements:
- Material reconnaissance
- Pulse number limitation
- Multi-pass irradiation
- Cooldown intervals

Thermo-mechanical „side effects“

Structural integrity risks

- Residual heat in laser ablation:
  - target melting (flat, large → sphere, small)
- Fragmentation risks:
  - Low heat conductivity → thermal stress
  - Frequent, rapid heating cycles→ aging effects
  - Strong shock and rarefaction waves

Molten aluminum target after repetitive laser irradiation



S. Scharring et al., Removal of Small-Sized Space Debris by Laser-Ablative Momentum Generation, ILRS Workshop, Canberra, November 2018

Simulation setup

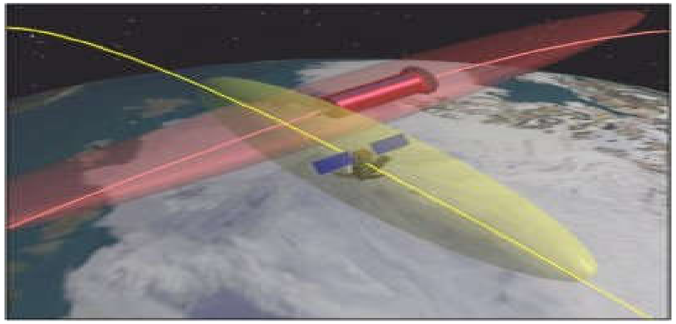
Laser specs: $E_L = 20\,kJ,\ M^2 = 2, \lambda = 1064\,nm, \tau = 10\,ns$
Transmitter: $D_{Telescope} = 8\,m,\ Str = 0.4$
Target: Al plate 2 x 2 x 0.1 cm, $\boldsymbol{\varepsilon = 0.09}$, $d_{spot} = 70\,cm$
Initial target temperature: $\boldsymbol{T_0 = 327.8\ (239.4)\ K}$ (dusk/dawn)
Circular orbit, 800 km altitude
Irradiation range: 30° - 100° elevation (3 minutes)
Monte Carlo study, up to 1000 samples each
Arbitrary target orientation, 0.42 µrad hit precision

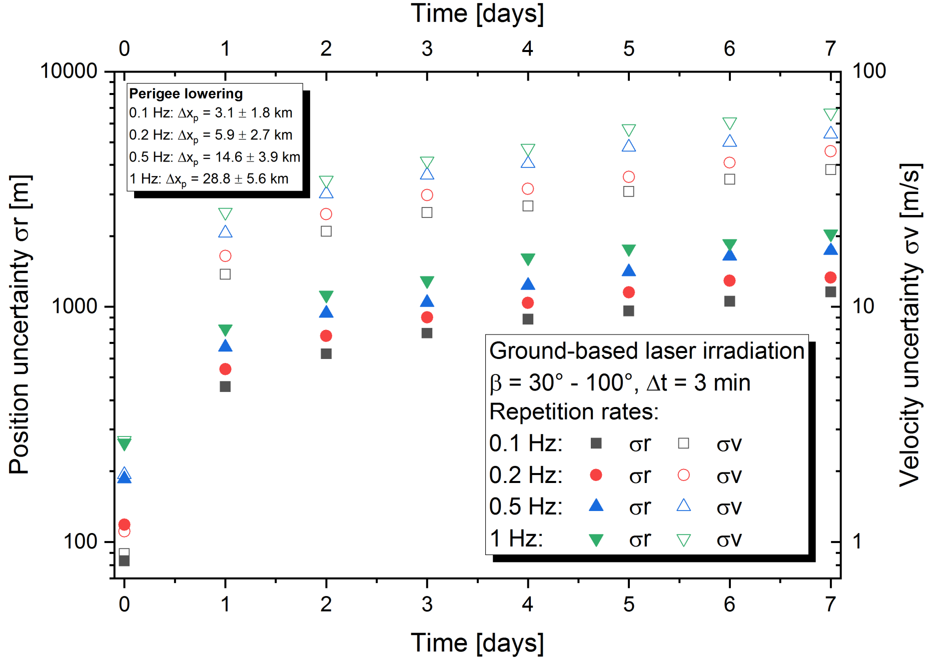
Requirements:
- Prior collision analysis
- Clearance for conceivable destination trajectories

Predictive collision avoidance

Collateral damage prevention for active missions

Multi-pass irradiation
→ need for long-term safe debris maneuvering
→ information on impact of Δv on orbit uncertainty needed





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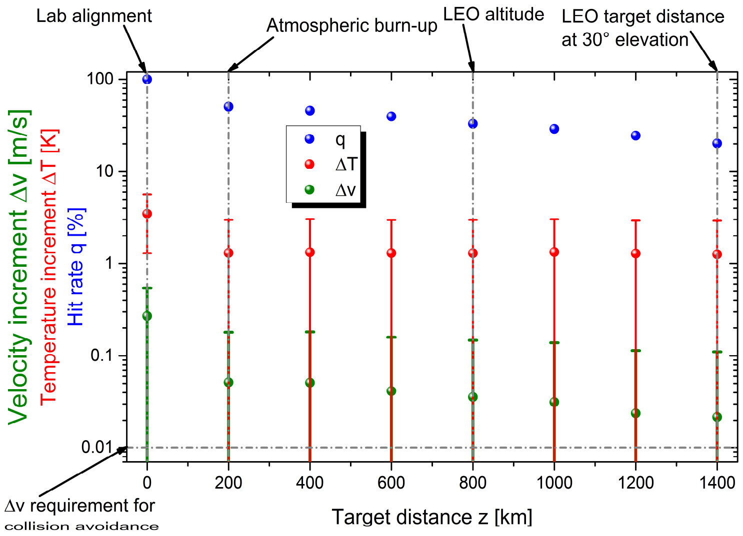
Circular orbit, 800 km altitude
Irradiation range: 30° - 100° elevation (3 minutes)
Monte Carlo study, up to 1000 samples each
Arbitrary target orientation, 0.42 µrad hit precision
Orbit propagation with ODEM software, $A/m = 0.1$

ODEM software used with friendly permission by DLR – Institute of Space Operations and Astronaut Training

Constraints of ground-based laser operation

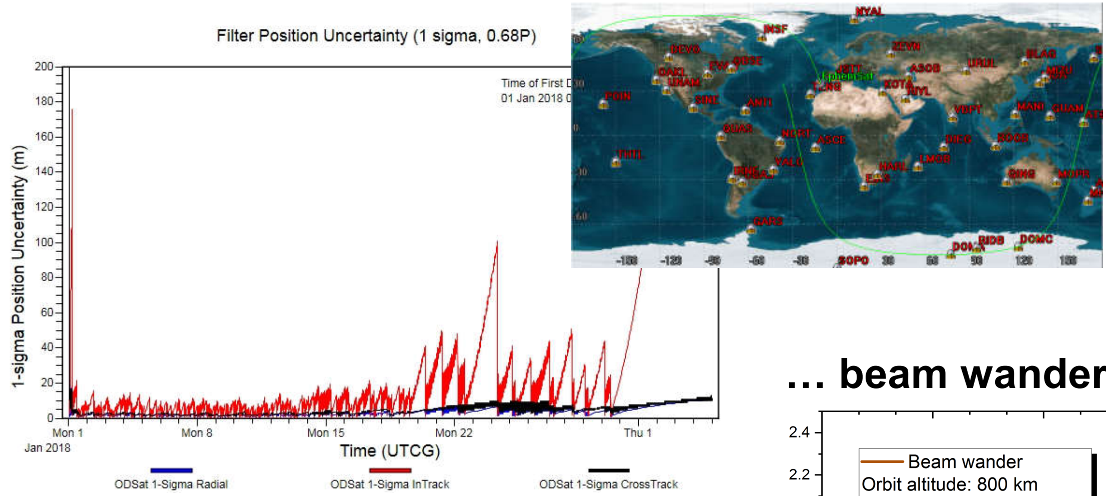
Requirements:
- target finetracking
- laser guide star
- tip/tilt correction

Hit rate, affected by…



Simulations on thermo-mechanical coupling
Laser: $E_L = 20\ kJ,\ M^2 = 2, \lambda = 1064\ nm, \tau = 10\ ns$
Transmitter: $D_{Telescope} = 8\ m,\ Str = 0.4$
Target: Al plate 2 x 2 x 0.1 cm, $d_{spot} = 70\ cm$
Monte Carlo study, 10,000 samples each
Arbitrary target orientation, 0.42 µrad hit precision

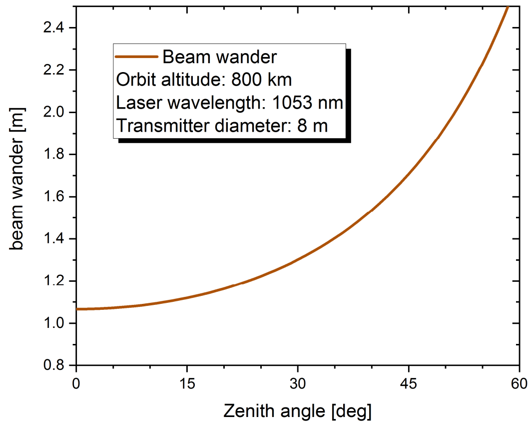
… debris tracking accuracy,



1-σ position uncertainty during laser ranging measurements to LEO (high inclination orbit) by a 46-station network; weather conditions: January, 11-year average

S. Scharring et al., Network performance analysis of laser-optical tracking for space situational awareness in the Lower Earth Orbit, AMOS paper (2019)

… beam wander,

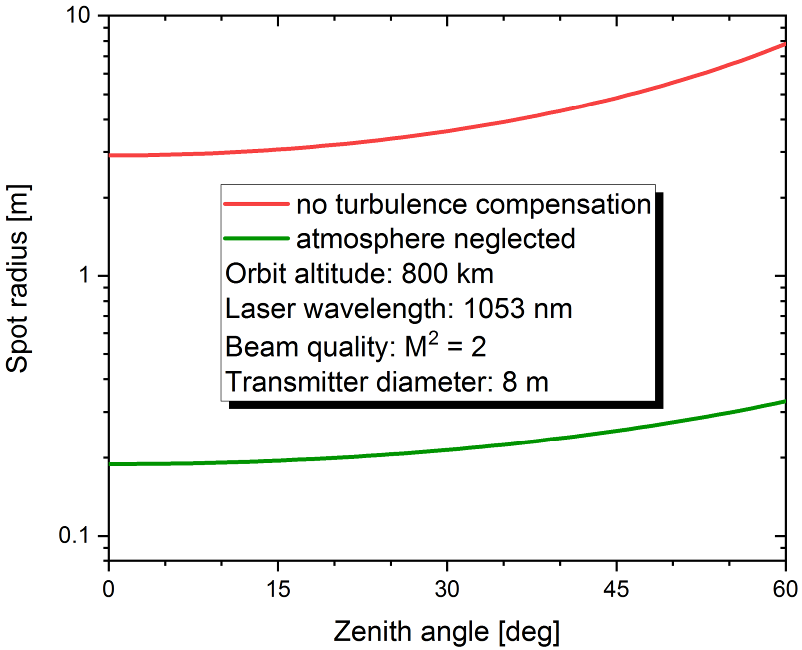


… and laser/transmitter pointing stability

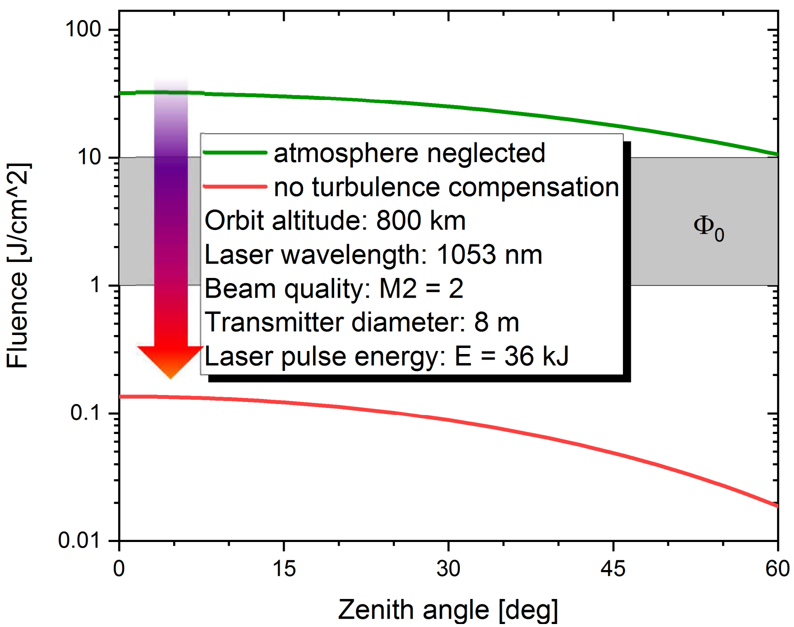
Requirement:
- adaptive optics

Beam broadening

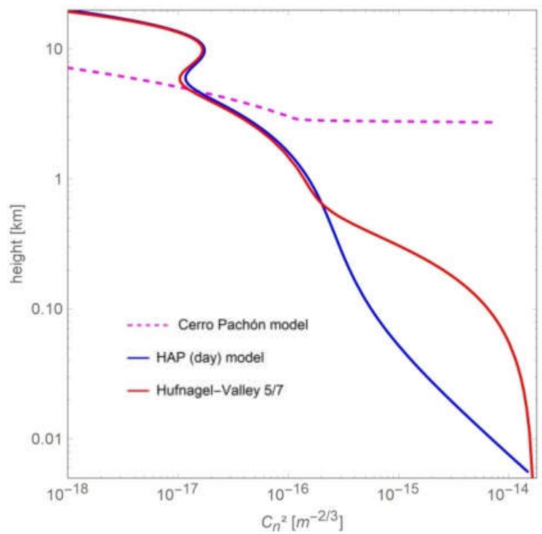
Spot size



Fluence



loss of function for uncompensated turbulence

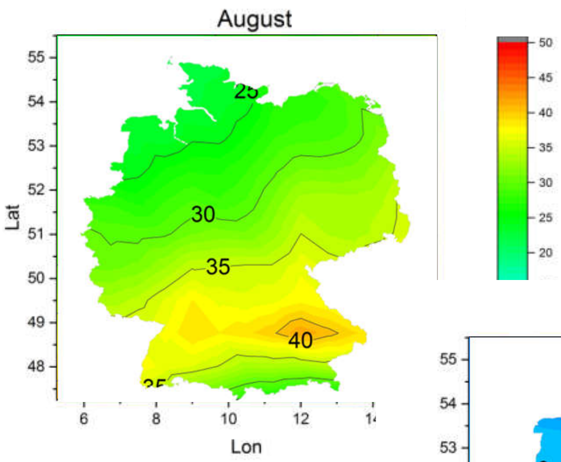


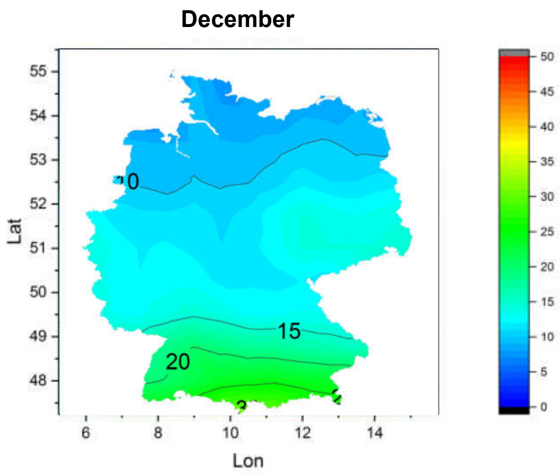
Laser pulse energy: 2 x 18 kJ, wavelength: 1053 nm (e.g., Laser Mégajoule beamlines)
$M^2 = 2$, transmitter diameter: 8m
Turbulence model: Hufnagel-Andrews-Phillipps (day)

Requirements:
- site weather analysis
- network redundancies

Weather conditions

Cloud cover: % Laser time fraction





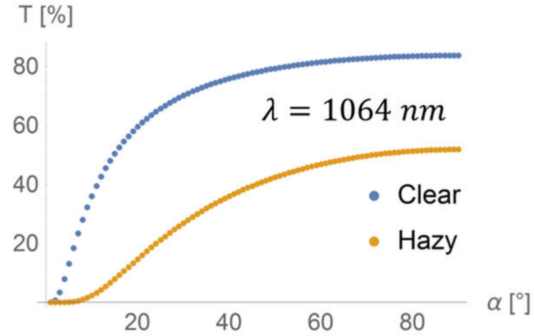
Criterion:
cloud coverage < 25%

Based on 3-hourly data with 0.75° lat / lon resolution from 2007 through 2017 kindly provided from the European Center for Medium Weather Forecast

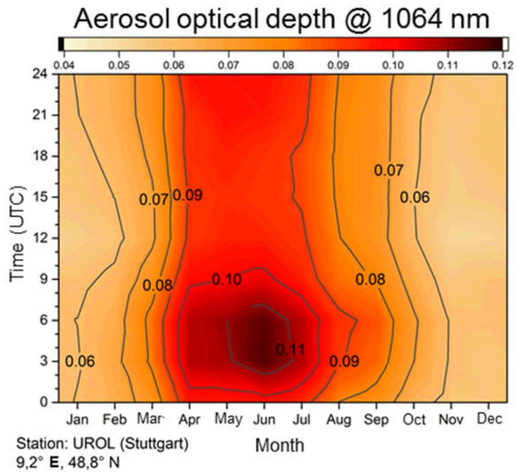
Extinction by aerosols and molecules

$$\mathrm{T}(z) = \exp \int_0^z \frac{-\gamma(z)}{\sin\alpha}\, dz$$

T Transmission
γ Extinction
α Elevation angle



Database:
R. A. McClatchey et al, Optical Properties of the Atmosphere (3rd ed.), Environmental Research Papers **411**, Air Force Cambridge Research Laboratories (1972)



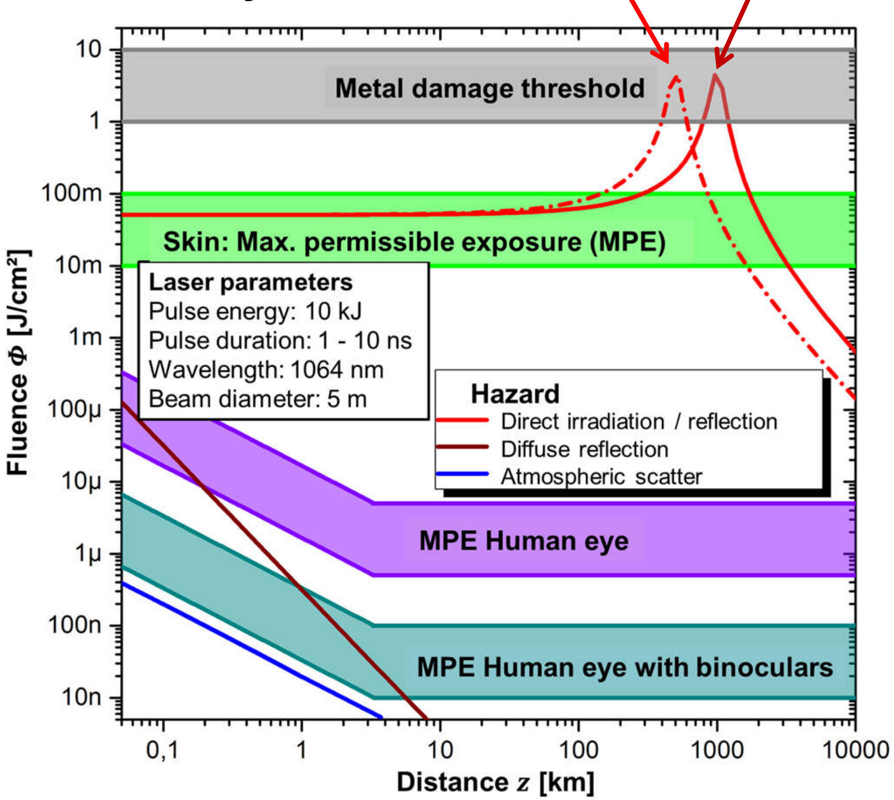
Based on 3-hourly data with 0.75° lat / lon resolution from 2007 through 2017 kindly provided from the European Center for Medium Weather Forecast

Requirements:
- predictive avoidance of unintentional irradiation

Laser safety

Hazard analysis

Focus at 500 and 1000 km distance, resp.



Risk mitigation

Ground:
- Elevation geofencing
- Restricted HEL area

Air:
- Virtual radar (ADS-B, FLARM)
- Beam sector primary radar
- No-fly zone

Space:
- Orbital traffic monitoring
- Publication of irradiation times
- Laser protection (astronauts, sensors)

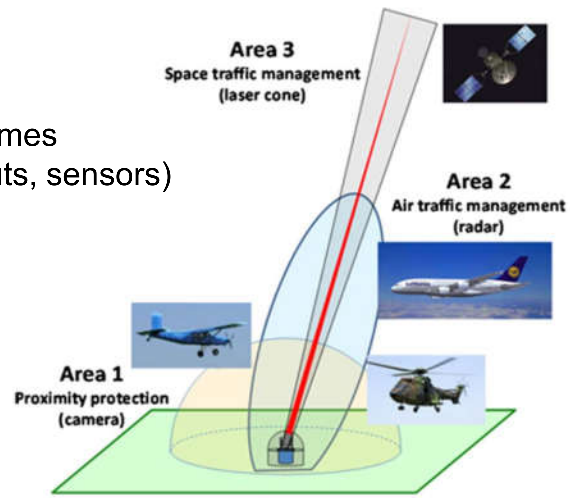


Fig. 15. Definition of the three safety areas.

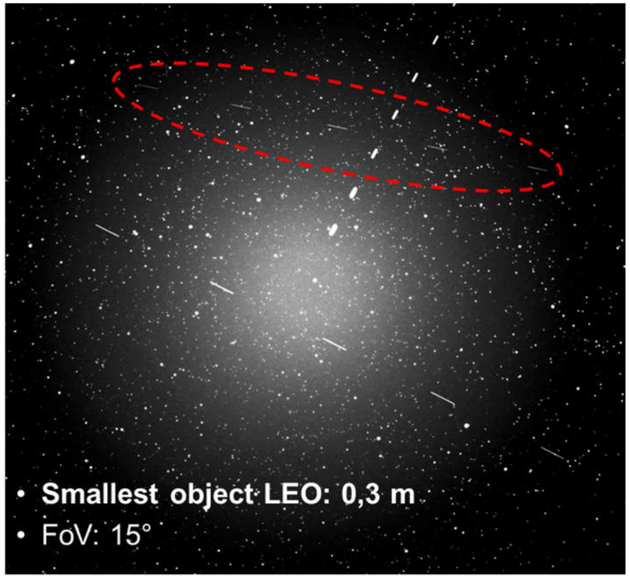
B. Esmiller, Appl. Opt. **53**(31): I45 (2014)

Current R&D steps in at DLR – Institute of Technical Physics

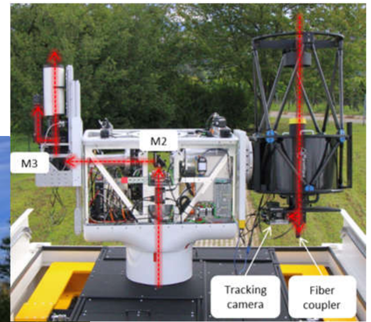
Space Situational Awareness

Passive optical tracking (staring sensor)

Megapixel Staring Cam

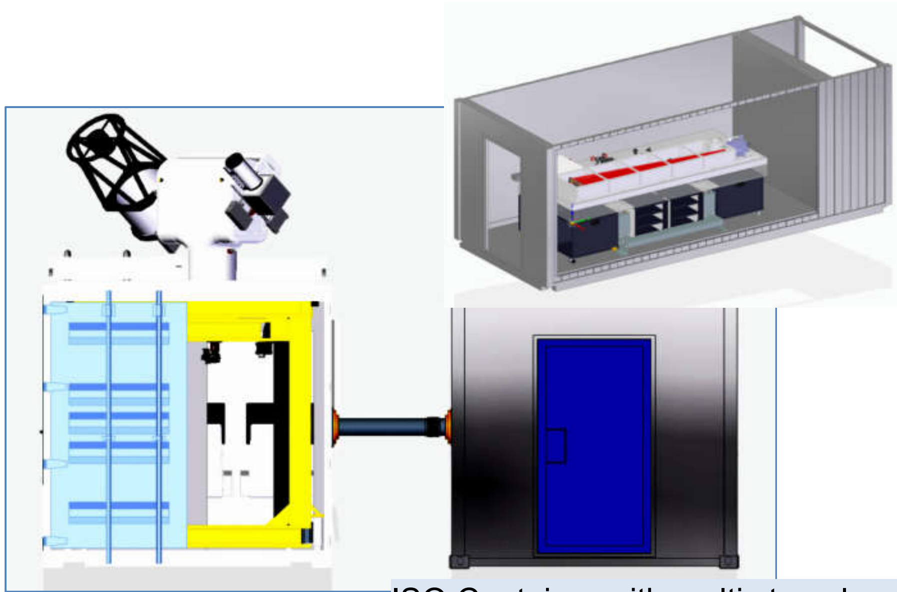


Laser debris ranging



Laser development

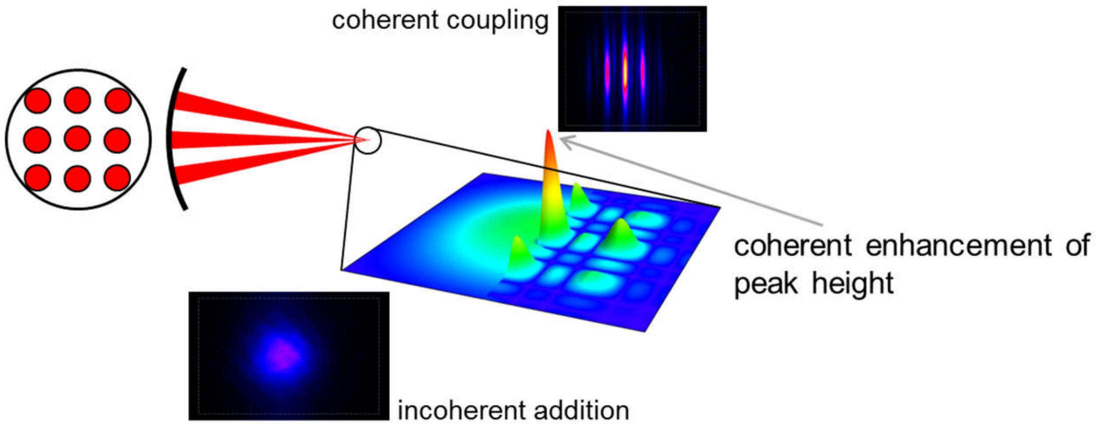
Lasers for small debris ranging (~10 cm)



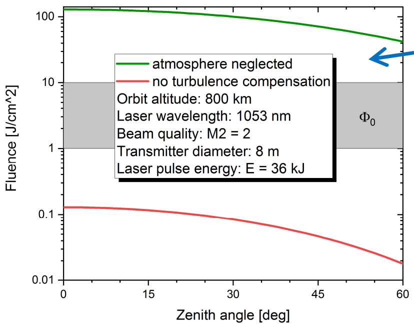
ISO Container with multi stage laser amplifier

Specs:
Average power kW level
multi kHz reprate, pulse energy 100 mJ,
nanosecond pulse duration

Removal laser concept: coherent beam coupling



Possible layout of a ground-based removal laser



- Laser pulse energy: ~ 20 kJ
- Wavelength: ~ 1 µm
- Pulse length: ~ 100 ps – 100 ns
- Pulse repetition rate: max. 1 Hz, e.g., subsequently operated single pulse beamlines

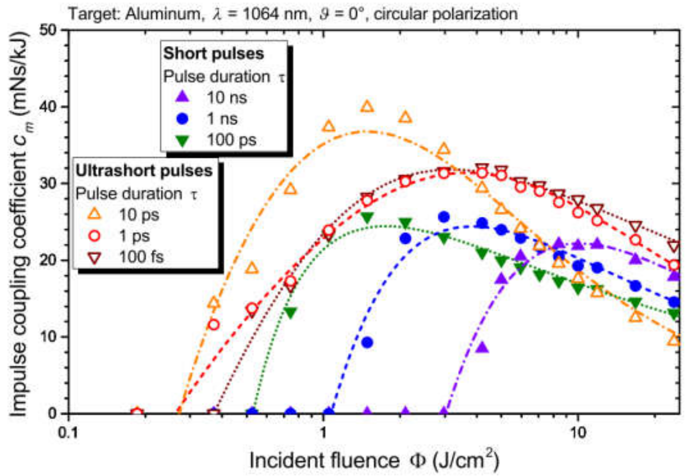
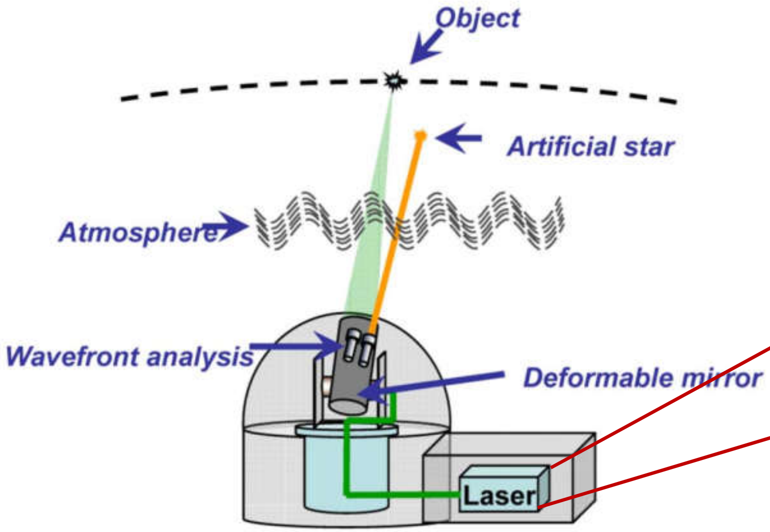


Fig. 3 Momentum coupling with aluminum targets at $\lambda = 1064$ nm for various laser pulse lengths. Results from 1-D HD simulations with Polly-2T.

S. Scharring et al., Opt. Eng. **58**(1): 011004 (2018)



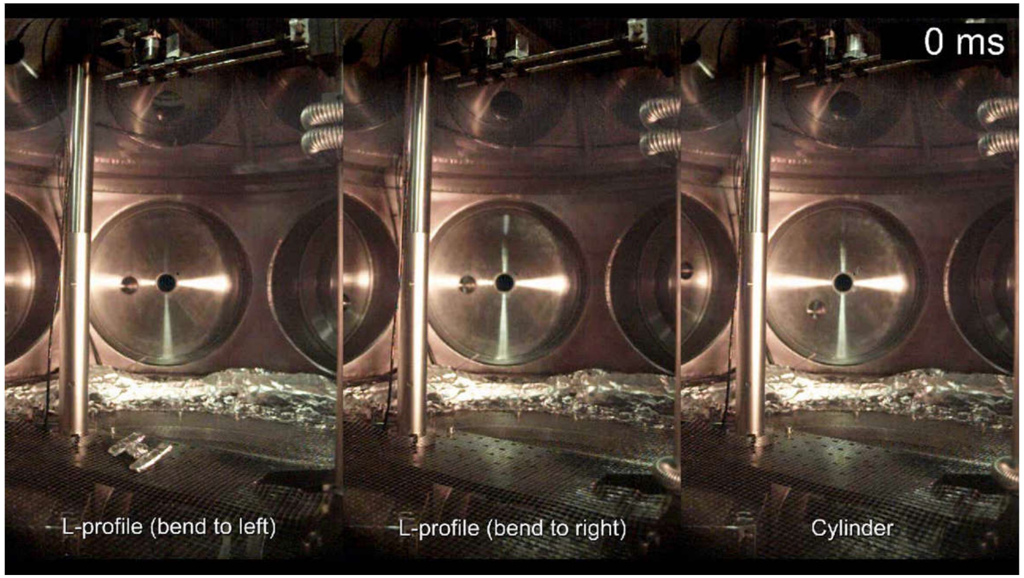
B. Esmiller, C. Jacquelard, H.-A. Eckel, and E. Wnuk, Space debris removal by ground-based lasers: main conclusions of the European project CLEANSPACE, Appl. Opt. **53**(31): I45 (2014), dx.doi.org/10.1364/AO.53.000I45

FIGURE 1. NIF is approximately 150 m x 90 m and seven stories tall. The two laser bays are shown on the upper-left portion of the figure. The switchyard (in red) is shown on the lower-right side, as is the spherical target chamber (in silver), into which the 192 beamlines converge.

A.M. Rubenchik, A.C. Erlandson, and D. Liedahl, Laser System for Space Debris Cleaning, AIP Conf. Proc. **1464**: 448 (2012): doi: 10.1063/1.4739899

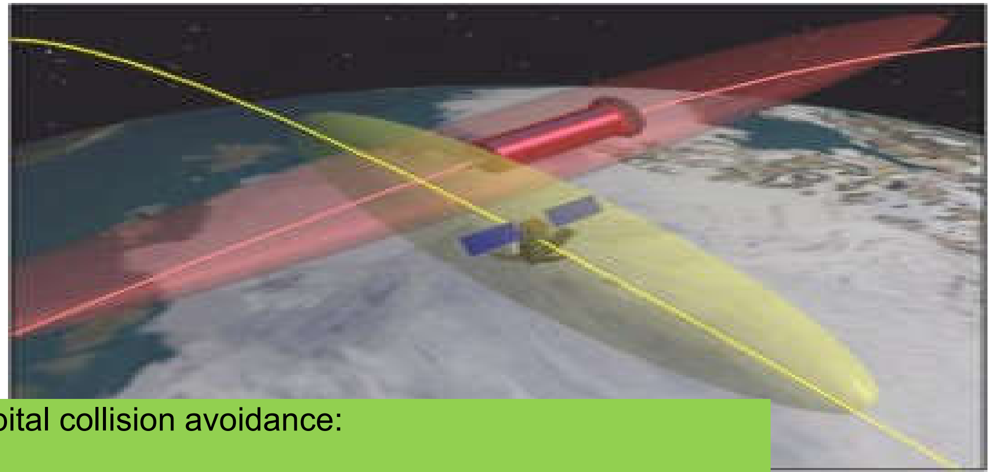
Laser-matter interaction: Collision avoidance

… with a single high energy laser pulse



Laser: $E = 80\ \mathrm{J}, \tau = 10\ ns, \lambda = 1064\ nm$
Spot fluence, size: $\emptyset = 3 \ldots 4\ cm, \Phi_{max} \approx 10\ J/cm^2$
Target dimensions: $A_{cs} \approx 1 \ldots 4\ cm^2, m \approx 1\ \ldots 3\ g$
Velocity increment: $\Delta v_{exp} = 0.25\ \ldots 2.8\ m/s$

R.-A. Lorbeer et al., Sci. Rep. 8: 8453 (2018)
https://www.nature.com/articles/s41598-018-26336-1



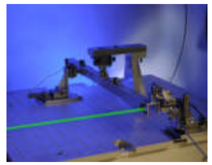
Orbital collision avoidance:

$\Delta v_{in-track} = -0.01\ m/s \rightarrow \Delta x_{in-track} = 2.5\ km/day$

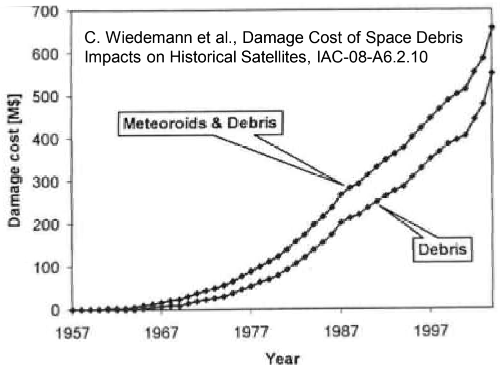
*J. Mason et al., Adv. Space Res. 48: 1643 (2011)

… or even by photon pressure with COTS cw lasers

Current research @DLR-TP:
ESA study SSA P3-SST-XV – Laser Ranging Systems Evolution Study (LARAMOTIONS)



Outlook – reverse roadmap (map of needs) for laser-based debris removal



Time (TBD)	Event	Remark
T_K	Onset of Kessler syndrome in LEO	Point of no return
$T_K - 5y$	Start of LDR operations	Less satellite outages
$T_K - 7.5y$	Implementation of an LDR station network	High financial invest
$T_K - 10y$	In-orbit verification of LDR principle with a single LDR station	Useful for collision avoidance
$T_K - 12.5y$	Technical readiness LDR components	Laser, transmitter and adaptive optics
$T_K - 15y$	Proof of technical feasibily of LDR components	
$T_K - 15y$	Validation and assessment of crucial issues in LDR	Efficiency, operational safety, politics
…		
now	Concepts and technology development	$May\ T_K - now \gg 15y\ !$

Thank you for your kind attention

Space Debris
Finnegan Scharring, 7 years
October 2017